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Enabling Post Combustion Capture Optimization – The Pilot Plant Project at Niederaussem

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Abstract

In 2007 RWE Power, BASF and Linde entered into a cooperation to develop an optimized post combustion capture technology for power plants. In mid-2009 a CO_2 capture pilot plant will be commissioned at RWE Power's lignite-fired power plant at Niederaussem, Germany. The pilot plant comprises all significant components of a large post combustion capture plant but on a smaller scale. Some capture process optimization measures are implemented that should increase the overall efficiency and reduce the costs of a commercial capture plant. The design of the pilot plant - engineering, procurement and construction by Linde - allows testing the performance and stability of optimized CO_2 solvents, which BASF is currently developing. On the basis of an elaborated solvent selection methodology (pre-selection, screening, etc.) comprehensive experiments are carried out in order to examine solvent performance, and some measures for the optimization of the process configuration are developed. The 18-month pilot plant testing programme will allow the performance of the optimized solvent and the process to be evaluated.

Keywords: CO_2 mitigation; post-combustion capture; amine scrubbing; solvent development; process optimization

1. Introduction

The background strategy for the development programme of RWE Power, BASF and Linde was derived from a joint feasibility study performed for a 1,100 MW_{el} lignite-fired power plant with integrated lignite pre-drying and post combustion capture (PCC) technology. The lignite pre-drying technique developed by RWE is a key technology for the next generation of lignite-based power plants, allowing the net efficiency of a power plant to be increased by a further 4%-points to more than 47%. A high starting efficiency is a prerequisite for CO_2 capture and keeps post combustion capture competitive in comparison with IGCC (Integrated Gasification Combined Cycle) with capture and oxyfuel technology. The feasibility study aimed at identifying the key drivers and their potential for the reduction of capture costs and capture energy penalty for subsequent testing and qualification in the PCC pilot plant. Two techno-economical key factors characterizing the performance of the process were defined as necessary conditions for a future application of the PCC technology, besides the necessity of appropriate political and legal conditions and public acceptance of CCS: The loss of efficiency caused by the integration of the PCC technology should be less than 10%-points (including CO_2 compression for pipeline transport to the storage site) and the CO_2 avoidance costs should be less than 30 €/t_{CO2}. The first criterion is based on the necessity of a resources-friendly use of coal for power generation and the second goal is geared towards the competitiveness of the PCC technology with storage in comparison to the simple purchase of CO_2 certificates.

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At present both criteria are not fulfilled by the PCC technology, particularly because of the very large, unpressurized flue gas stream of a coal-fired power station that has to be treated and due to its special composition that differs from CO_2-rich gas streams. These are normally cleaned by CO_2 scrubbing in the chemical industry. Therefore the available PCC technology is not adapted to the requirements of a full-size application in coal-fired power plants. But the results of the feasibility study have also shown that both general goals could be accomplished by an optimized PCC process on the basis of a new scrubbing solvent. In addition, the work performed during the development of the new PCC concept allowed the identification of several potentials that could contribute to a substantial reduction in the high investment costs of a capture plant.

Therefore, the development programme started with a pre-selection and pre-testing of the new improved solvent and a definition of the pilot plant design.

2. Solvent development

Currently available solvents for the removal of CO_2 from flue gases do not fulfil all the demands of post-combustion capture technology. At present, the state of the art is the use of monoethanolamine (MEA) to capture CO_2 from the flue gas. However, this process was originally developed for the production of CO_2 and not for the capture of CO_2 for CCS purposes.

There are several ways in which an ideal post combustion capture process could improve upon a generic MEA capture process. Improvements are possible for the solvent itself, and also for the process configuration. Starting with the characteristics of the solvent, the following aspects are of most interest:

- Low regeneration duty
- High stability against oxygen and thermal stress
- Low vapour pressure to reduce solvent losses
- High cyclic capacity to reduce the solvent circulation rate
- High reactivity to CO_2/fast reaction kinetics
- Uncritical safety data (e.g. non-toxic, high flash and ignition point)
- Good availability and low cost

Based on these needs, a solvent screening programme has been started by BASF to evaluate different amines in the BASF portfolio for their potential use as a solvent for a post combustion process. The screening phase can be divided into three steps:

- Pre-selection of amines based on easily available data, such as material safety data sheets, vapour pressure, molecular mass, and alkalinity (reactivity) data. About 400 substances were screened in this step and about 70 potential candidates were identified and tested in the next step.
- Lab screening, experimental determination of the phase equilibrium, reaction kinetics and stability. Here, not only the 70 pre-selected substances, but also mixtures of these substances were investigated.
- Miniplant**:** performance tests to verify the lab experiments completely.

The screening procedure will end in a pilot plant phase testing the best solvent candidates on a technical scale. Some technical details of the pilot plant testing are presented in this paper. In addition, the steps leading to the pilot plant tests are of interest, especially the lab experiments selected to investigate and estimate the stability, cyclic capacity and reaction/mass transfer rate of the pre-selected substances. Based on these investigations it is clear that some of these demands for such a solvent are mutually exclusive. Often a high reactivity – fast reaction kinetics – can be found in a combination with a high regeneration duty. Stable solvents are less reactive than more unstable solvents. Thus it is expected that a potential solvent will consist of more than one active component. The combination of solvents will maximize the advantages and minimize the disadvantages of the component mixture.

2.1. Cyclic capacity

The cyclic capacity is determined and the regeneration duty estimated by phase equilibrium measurements. The equilibrium loading of CO_2 for different CO_2 partial pressures is therefore measured for 40 °C (absorber) and 120 °C (stripper).

The cyclic capacity is defined as the difference between the loadings in the absorber and desorber sumps. It is an important factor for the sizing of the piping, pumps, heat exchangers, and the diameter of the stripper. With the help of equilibrium data (see Fig. 1) the cyclic capacity can be easily estimated.

Firstly a temperature of 40 °C in the absorber bottom is assumed where the equilibrium loading for a CO_2 partial pressure is 13 kPa (a typical value for the flue gas of hard coal- or lignite-fired power plants). Secondly, a temperature of 120 °C in the stripper sump is assumed, where the equilibrium condition for a CO_2 partial pressure is 10 kPa. The cyclic capacity can then be calculated as the difference between these two loadings.

In Figure 1 the evaluation of the cyclic capacity of MEA and one of the screened solvents (XYZ) is shown. A high cyclic capacity can be reached by a significant temperature dependence of the solvent's equilibrium loading. For the example shown, the screened solvent (XYZ) has about 50 % higher cyclic capacity than MEA.

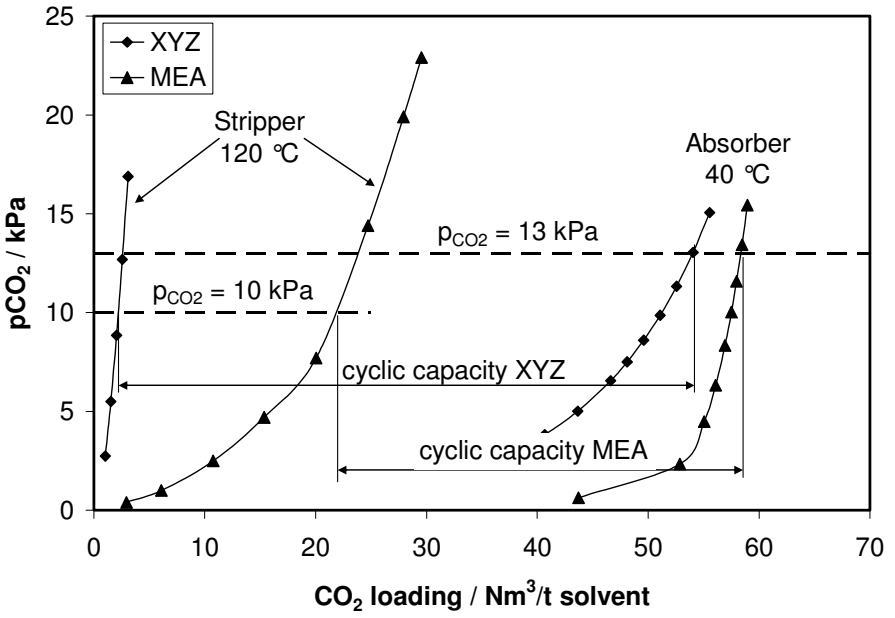

Figure 1: Determination of the cyclic capacity of monoethanolamine (MEA) and one of the screened solvents (XYZ)

2.2. Regeneration duty

In addition to the cyclic capacity of the solvent, the required regeneration duty can be assessed by means of the phase equilibrium measurement. In the McCabe-Thiele diagram, the gradient of the operating line can be related to the specific regeneration energy of the solvent.

Under the conditions in the stripper sump, the operating line can be approximated by the equilibrium curve, so that the gradient of the equilibrium curve is nearly equal to the gradient of the operating line. The gradients of the equilibrium curve and the operating line, respectively, are inversely proportional to the necessary strip steam rate. The required energy for the strip steam rate is the main contribution to the total energy duty; other energy contributions are, for example, the heating up of the solvent and the reflux flow.

It is advisable to work with the inverse factor of the gradient since this is directly proportional to the required strip steam rate per kg of solvent. The division of the inverse factor of the gradient by the cyclic capacity of the solvent leads to a value that is directly proportional to the strip steam rate per kg of captured CO_2. More details of these methods are also described by Notz et al. [1].

2.3. Mass transfer rate / Reaction kinetics

The mass transfer rate of carbon dioxide into the different solvents is investigated by experiments in a double-stirred contactor. The mass transfer rate for a reactive absorption consists of two contributions: physical mass transport and chemical reaction kinetics. The sum of these contributions is measured in these experiments.

The double-stirred cell consists of a CO_2 tank, the cell itself, thermostat, dosage valve, and pressure measuring device. After filling and temperature adjustment of the solvent in the cell, CO_2 is discharged into the upper part of the cell via the dosage valve under a constant pressure. For the investigation, the temperature and pressure are adjusted to typical absorber conditions. During the experiment the solvent is continuously loaded with CO_2, so that the absorption rate decreases over the duration of the experiment. At the end of the experiment, conditions approximating an equilibrium are achieved, and the flow rate of CO_2 is almost zero.

In Figure 2, the absorption rates of various solvents are compared to the CO_2 loading of the solvent. The absorption rate is calculated from the registered volumetric rate of CO_2 and the solvent filled into the cell. The loading of the solvent is determined from the accumulated amount of CO_2 discharged to the cell and the mass of solvent in the cell.

2.4. Oxygen stability

The third aspect that is evaluated in screening experiments is the oxygen stability of the different solvent candidates. For many applications, such as synthesis gas and natural gas treatment, this point is not relevant, as these gases are usually free of oxygen. However, the flue gas of all fossil-fired power plants contains a significant amount of O_2.

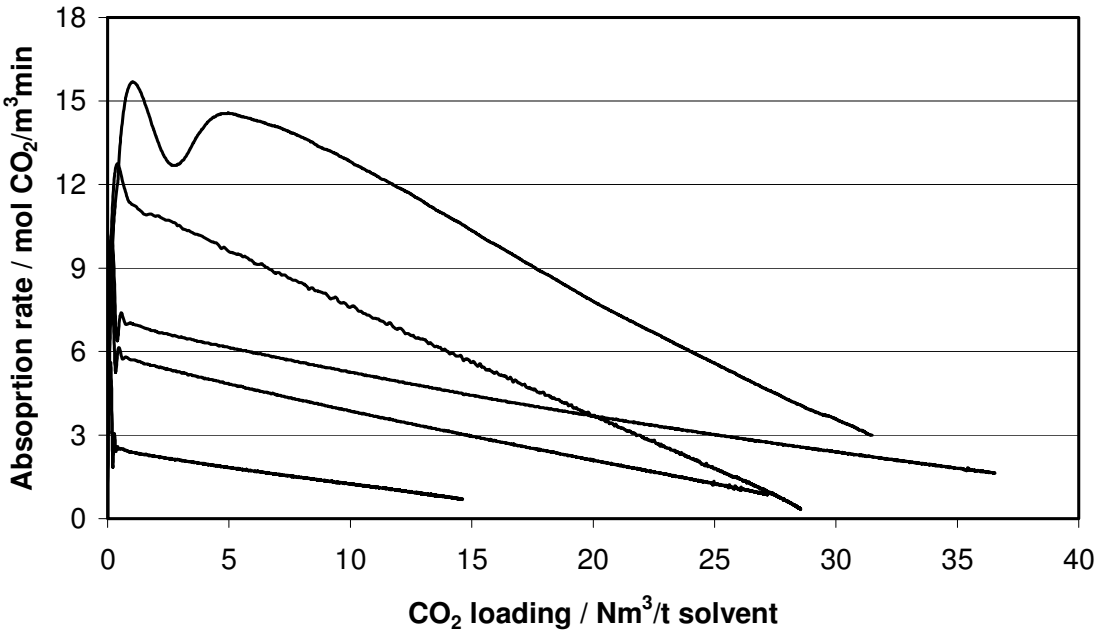

Figure 2: Absorption rate of different solvents measured in a double-stirred cell under absorption conditions

In a stress test under an O_2-containing atmosphere the solvents were screened for their O_2 stability. A small quantity (approx. 150 ml) of each different solvent was placed into a small glass vessel and heated to an elevated temperature.

CO_2 and air are blown into the liquid via a diffuser stone. The degradation of the solvent is determined by GC analysis. Based on this method, a ranking of the different solvents' relative stability is obtained. An absolute value can only be evaluated under real conditions in the pilot plant.

2.5. Process optimization

In addition to the perceived demand for new solvents for PCC processes, the process itself needs to be optimized. For the new solvents, the available data are presently insufficient to create a rate-based model and use this model to simulate different process conditions and configurations. As a result, MEA has been selected for such a study.

For the simulation, the BASF in-house software CHEMASIM is used. One part of CHEMASIM is a non-equilibrium model, including the rigorous calculation of heat and mass transfer between the gas and liquid phases, including the effects of the various chemical reactions. A more detailed description of the rate-based model is given in [2]. The necessary model parameters are determined on the basis of phase equilibrium measurements and reaction kinetic data. The model is also validated by miniplant and pilot plant runs [3, 4].

By way of example, Table 1 compares two different process configurations and sets of parameters, and a significant improvement of the process can be attained by this optimization. The specific energy duty can be reduced by 12 % by cooling down the flue gas and using an interstage cooler. Such an optimization procedure will also be performed with the new solvents following the miniplant and pilot plant runs.

Table 1: Result for process optimization using MEA: Impact of flue gas temperature and interstage cooler

Case		**base**	**optimized**
Flue gas temperature	[°C]	46	30
Lean solvent temperature	[°C]	40	40
Interstage cooler	[-]	No	Yes
Stripper pressure	[bar a]	1.8	1.8
Relative regeneration duty	[%]	100	88

3. Capture plant optimization

In addition to the stability and performance of the solvent, the plant concept itself, including each process step and the sequence of steps, plant layout, equipment design and material selection, has a significant influence on the overall plant costs. Therefore, the development project includes an accurate analysis of all process steps in order to understand which of them are really required, which can be optimized and which can be optimized by means of a combination of equivalent ones.

3.1. Flue gas blower configuration

An example of this process step analysis is the configuration of the flue gas blower that is required to overcome the pressure drop of the flue gas in the CO_2 wash column. Different options for positioning the flue gas blower in the process, e.g. upstream or downstream the CO_2 wash column, have been considered and evaluated. Furthermore, the option of compensating the pressure drop of the flue gases by means of an enlarged ID fan upstream the FGD unit (flue gas desulphurization) has been considered.

3.2. SO_x pre-scrubber

Another process step with relevant optimization potential is the pre-wash section. This section, consisting of a wash column operated with a NaOH solution that comes into direct contact with the flue gases, has the purpose of removing SO_x traces down to few ppmv in order to avoid a reaction of these components with the solvent, which would increase the solvent losses and therefore the make-up requirements. Furthermore, in the pre-wash section the flue gas is cooled down to appropriate temperatures before entering the CO_2 scrubbing column. A possible option which would allow reducing the actually required significant NaOH quantities would be to enhance the performance of the FGD unit located upstream the CO_2 wash unit, so that very low SO_x concentrations are reached in the flue gas.

3.3. CO_2 compression and drying

From an energy consumption point of view, the CO_2 compression section, including the CO_2 drying unit, is a particularly relevant step of the entire PCC technology, as its power consumption crucially determines the overall power demand of the process. Therefore, particular attention has been attached to the optimization of this concept and its integration in the overall power plant. Different CO_2 compression concepts, such as multi–stage compression with intermediate cooling or compression and liquefaction, followed by pumping to the final pressure, are analyzed and compared in detail.
In order to avoid possible corrosion phenomena and the formation of hydrates the present requirements for the transport of CO_2 include very low H_2O levels. Therefore a drying unit has to be implemented.
Two possible options are considered and investigated:

- glycol-based wash unit
- molecular-sieve adsorption unit

If the molecular-sieve adsorption unit allows a reduction of the CO_2 water content down to very few ppmv, its power consumption is significantly higher than in case of a glycol-based wash unit. Therefore, the selection of the drying technology requires close consideration. In both cases, an important issue that calls for a careful evaluation is the position of the drying unit located at an intermediate CO_2 compression stage. In general, the higher the CO_2 pressure is, the lower is the remaining water content in the CO_2 that has to be removed. This generally has a positive effect on the size of the drying unit. On the other hand, since the costs of the components operating at higher pressure might increase, an estimation and comparison of the different possible options is necessary to find an optimized solution.

3.4. Plant design and alternative materials

The decisive question for the plant layout is the number of parallel trains required. It is obvious that a reduced number of trains will contribute significantly to a reduction in overall capital costs. Together with other factors like scale-up-risk, redundancy and operational availability, one of the determining factors in finding the required number of trains is the availability of the equipment in the required dimension. For a full-scale plant, the low-pressure flue gas flow and its resulting enormous effective volume represent the challenge for the mechanical and hydraulic design of the CO_2 wash column.

The approach adopted during the preliminary feasibility study was to set an upper limit for the size/diameter of the wash column based on the experiences of Linde and manufacturers of column internals. In the present phase, the focus is on the possibilities of "expanding" these limits and on the further research activities required to minimize the involved risk. Of special interest in this context is the understanding of the hydraulic behaviour, i.e. the homogenous distribution of the vapour as well as the correct vapour/liquid ratio in the column. Due to the complexity of the total system and the envisaged size, first results indicate that a CFD analysis alone will not be satisfactory in terms of risk minimization. Therefore an appropriately sized demonstration plant should be used as final proof before commercial application.

As already mentioned above, material selection can also help to substantially reduce investment cost. For this purpose, the material used for the columns and for the internals has to be checked. To increase the prediction accuracy for the behaviour of alternative materials (other than stainless steel), several probes will be installed in the pilot plant.

4. Niederaussem pilot plant project

The first item on the pilot plant testing programme is the validation of the performance of the optimized BASF solvents under power plant operating conditions. This includes in particular energy consumption for regeneration and long term stability of the solvent. Additionally the tests should confirm the optimized process concept, and the results will deliver the input data for the engineering of a demonstration plant and a precise cost determination. Therefore comprehensive process parameter studies will be performed to determine the optimum operational set point. Moreover, the testing programme will be accompanied by an extensive sampling, analysis and measurement programme to identify and evaluate the solvent degradation velocity and the resulting solvent losses, the pureness of the captured CO_2, the emission of volatile compounds and the accumulation of solid material in the process that has not been removed by the electric precipitators and the pre-scrubbing unit (fly ash particles, gypsum particles coming from the FGD). Figure 3 gives an overview of the process steps in the Niederaussem pilot plant.

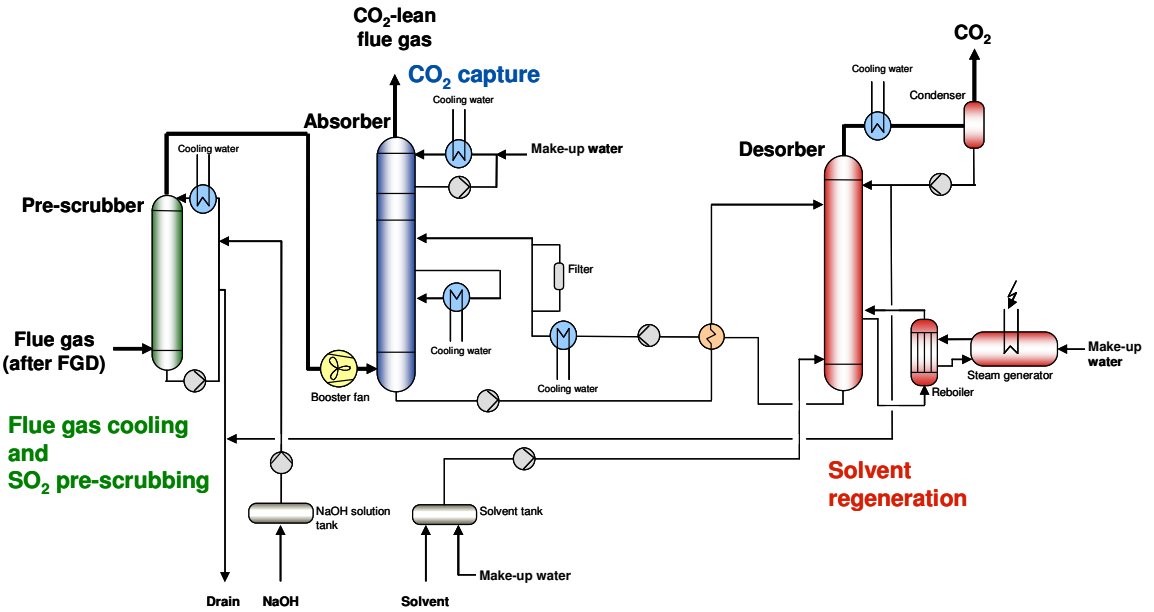

Figure 3: Process diagram of the pilot plant in Niederaussem.

The size of the pilot plant that is under construction at the lignite-fired 1,000 MW_{el} BoA 1 unit at Niederaussem was defined by the minimum size allowing reliable results to be obtained for the validation of the PCC process performance. Up to 300 kg/h CO_2 from a flue gas bypass of the lignite-fired unit will be captured, and a capture rate of typically 90 % will be reached. The diameter of the pilot plant absorber column was limited to the size required to obtain representative results. It is fitted with optimized plant technology, e.g. interstage cooling equipment. The height of the pilot plant will nearly be identical to that of a full scale capture plant, i.e. approx. 40 m. The plant will include special features for process optimization and more or less all components of a commercial plant concept. In the first section of the pilot plant, acid components of the flue gas will be removed in a NaOH pre-scrubber and the flue gas can be cooled down if required. The steam for solvent regeneration is supplied by an electric driven steam generator. This configuration guarantees an additional option for the precise determination of the heat demand for solvent regeneration. The product CO_2 stream is fed back to the unit's flue gas duct. The design of the pilot plant allows exchanging the packing materials at a later stage of the programme and adapting the equipment to the requirements of the solvent.

Pilot plant operation will start in mid-2009 and will last 18 months. Besides the parametric studies, the testing phase will also include long-term testing phases under constant operational settings.

The Niederaussem power plant is ideally suited as a site for the post combustion capture pilot plant shown in Figure 4 and offers outstanding options for the testing of the PCC technology in combination with advanced power plant technology. With a net efficiency of over 43%, BoA 1 is the most advanced and efficient lignite-fired unit worldwide with state of the art electric precipitators and FGD technique.

4.1. Testing with flue gas from the combustion of pre-dried lignite

A lignite pre-drying plant was constructed at BoA 1 and started demonstration operation in mid-2008. Therefore the BoA 1 site allows testing the CO_2 scrubbing process on flue gas from pre-dried lignite combustion. The effect of the reduced flue gas temperature on capture plant performance will be examined in comparison with normal plant operation based on the combustion of raw lignite. Sensitivity analyses investigating the influence of the flue gas temperature on the need of flue gas cooling and interstage cooling, in particular, can be performed and will provide information on optimization opportunities.

4.2. High-performance FGD

Additionally, in a parallel project at BoA 1, a high-performance FGD pilot plant will be operated at the same time as the PCC pilot plant, which allows flue gas with a very low SO_2 content to be fed to the CO_2 absorber. The otherwise necessary addition of NaOH into the recirculating water flow of the SO_2 pre-scrubber/direct contact cooler unit can be dispensed with in this advanced desulphurization technology. The overall goal is to make the pre-scrubbing process step dispensable, with operating and investment costs being equivalent to those of a conventional FGD. Special attention should be paid to dust and aerosols that enter the CO_2 absorber.

4.3. Capture plant integration

In parallel to the pilot plant testing programme the design of a commercial-scale PCC plant for a 1,100 MW power plant with pre-dried lignite technology will be further developed. The focus of this work is on efficiency enhancement of the power plant with integrated CO_2 capture and cost reduction. On the basis of the testing results, extensive modelling work will be accomplished to optimize the heat supply for solvent regeneration and to improve the integration of waste heat into the water-steam cycle of the power plant.

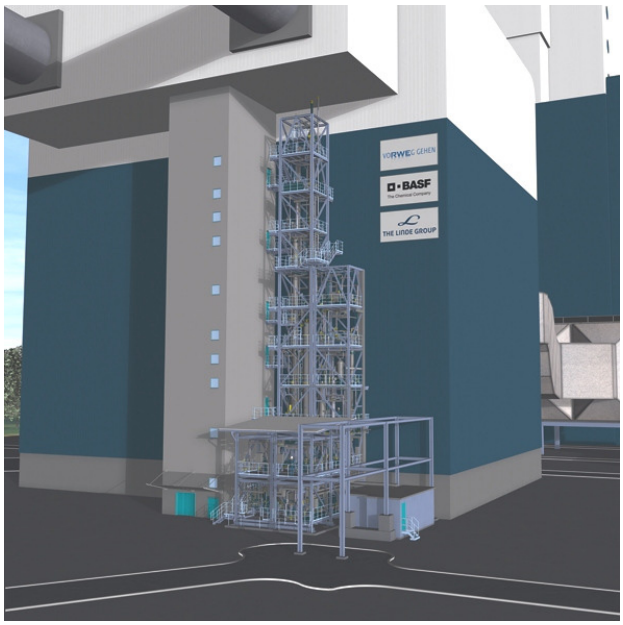

Figure 4: The CO_2 post combustion pilot plant in Niederaussem is located at the rear of the 1,000 MW BoA 1 unit's FGD building.

5. Conclusion

A new optimized PCC process on the basis of an advanced solvent with significantly higher cyclic capacity than MEA and lower energy demand for its regeneration has the chance to reduce the loss of efficiency caused by CO_2 capture and compression down to less than 10%-points. The additional use of cost-effective equipment and an efficient design of the capture plant offer the opportunity to meet the cost objective we have defined for our PCC development program. This includes the optimization of the interfaces between power and capture plant, e. g. the flue gas blower/FGD/direct cooler configuration, and waste heat integration into the process. The goals are ambitions but seem to be achievable as things stand today.

The overall goal of the PCC development programme is to gain access to a commercial PCC technology by the mid of the next decade so that it can be applied in the power plant generation that will start operation from 2020.

Provided that the pilot phase is completed successfully, this pilot plant project is planned to be immediately followed by a demonstration phase during which a large-scale demonstration plant will be built.

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